proportional change in the transit time. A change in temperature also changes the transit time, but in a very predictable manner. Hence the sensor acoustically monitors, in real time, changes in the average temperature along the cross section of the chamber wall, with a real-time temperature compensation applied to the measurement just described. The sensor system consists of a personal computer that houses the electronics and the transducer module. The transducer module is attached to the outer wall (or window) at the chosen location on the process chamber. The transducer module is a cylinder 2 in. in diameter and 2 in. in height. The primary use of this sensor is for determining and optimizing the chemistry, frequency, and duration of clean cycles for etch and deposition tools.

III. WAFER-STATE SENSORS

As stated previously, process-state sensors have been used predominantly for endpoint determination and fault detection and, in some recent cases, for dynamic process control. But clearly, wafer-state sensors provide more direct information for all these tasks. Such wafer-state sensors are slowly being integrated into processing tools, paced by issues of customer pull, sensor reliability, and cost of integration. The following is a description of the wafer-state sensors that have been, or are currently, overcoming these barriers and are being integrated into OEM tools.

A. Film Thickness and Uniformity

The thickness of optically transparent thin films (silicon, dielectrics, resists) on a reflective substrate is measured via the analysis of the interaction of electromagnetic radiation with such a film or film stack. These methods rely on single-wavelength (laser) or spectral (white light) sources, impinging on the sample at normal incidence (interferometry and reflectometry) or at some angle off-normal (reflectometry, ellipsometry). The wavelength range is from the UV through the IR. The interaction of the light with the material can be detected through a polarization change (ellipsometry), a change in the phase (interferometry), or a change in the reflected amplitude (reflectometry). Optical models are used to extract the different physical parameters of the films (e.g., thickness) from the known optical indices of the individual layers. These techniques are well-established standard methods for off-line film thickness measurement, and hence the methods will be described only briefly. The emphasis will be on the deployment of these techniques as sensors in OEM tools.

1. Optical Sensors

The spectral reflectivity of transparent thin films on reflective substrate materials is modulated by optical interference. The effect of the interference on the measured spectrum is a function of the film and substrate refractive indices. If the dispersion components of the refractive indices are known over the wavelength range, the thickness of the surface film can be found using a Fourier transform technique. For thin layers (< 100 nm), the method of spectral fitting is very effective. Once the film thickness has been found, a theoretical reflectance spectrum can be determined and superimposed on the measured spectrum. This ensures a very high level of reliability for the film thickness measurement.

a. Reflectometry Technique

Theory of operation. The thickness of films on a silicon wafer is measured by means of spectrophotometry, utilizing the theory of interference in thin films (51). The basic procedure is to measure the spectral reflectance of the desired sample. The spectral data is then interpreted to determine the thickness of the top layer of the measured stack. The actual reflectance $R_{act}(\lambda)$ is measured and fitted to $R_{theor}(\lambda)$ to find the thickness (d) of the last layer. $R_{theor}(\lambda)$ is calculated according to the specific optical model of the measured stack. The "goodness of fit" parameter measures the difference between the measured and the theoretical results and is used as a criterion of correct interpretation. Figure 18 shows a graph of $R_{theor}(\lambda)$ for a layer of 10,000-Å SiO_2 on Si substrate. The fitting algorithm used for data processing has to treat several issues, such as: spectral calibration, noise filtering, recognition of characterizing points (minima, maxima, etc.), and calculating a first-order approximation for the thickness and the final fine fitting.

Optical overview. The optical path of one specific reflectometer (52) is shown in Figure 19. In this case, the specular reflection is monitored at the incident angle normal to the wafer surface, and the radiation source is in the visible range. Briefly, the light emitted from the lamp (11) travels through an optical fiber (10) until reaching a condenser lens (9). The light beam then reaches a beam splitter (3), where it is split; half of the light passes through the beam splitter, while the other half is reflected downwards, focused by a tube lens (2) and an objective lens (1) onto the target (wafer). After being reflected by the target, the light beam travels back through the objective lens (1), tube lens (2), and beam splitter (3) until it reaches a "pinhole" mirror (4). From there, the light is sent in two directions:

1. A portion of the light (the image of the wafer surface) is reflected from the "pinhole" mirror (4), focused by a relay lens (5) onto a CCD camera (8), where it is processed and sent to the monitor for viewing by the operator.
2. The light that passes through the "pinhole" is also focused by a relay lens (6) and then reflected by a flat mirror toward the spectrophotometer (7), which measures the spectrum of the desired point. This information is then digitized and processed by the computer for the computation of film thickness.

This spectrophotometer also includes an autofocusing sensor for dynamic focusing on the wafer surface during the movement of the optical head over the wafer.

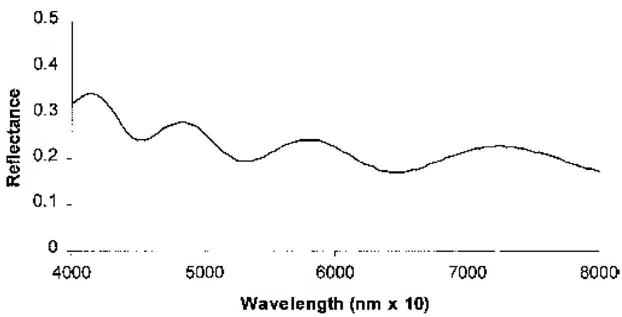

Figure 18 Reflectance of SiO_2 on Si in water. (From Ref. 51.)

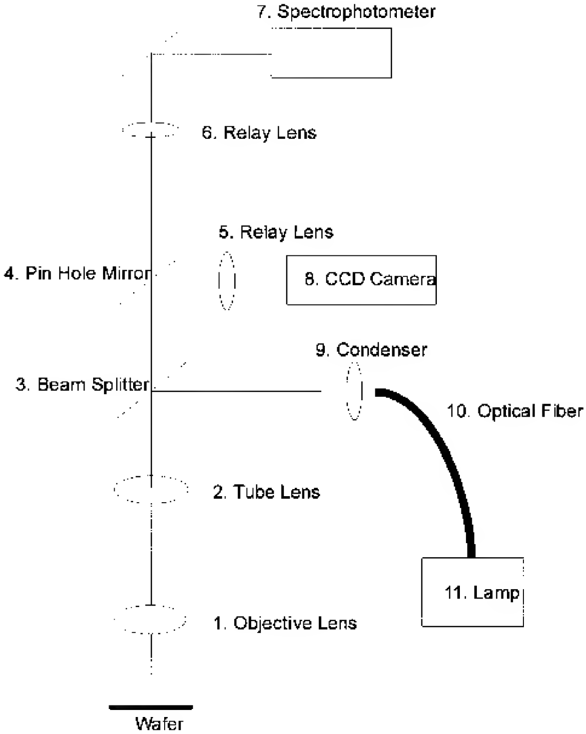

Figure 19 Optical path of light beam in NovaScan 210. (From Ref. 51.)

System integration, in-line measurement. While this chapter is focused on in situ metrology, there are some well-established in-line measurement techniques that are worth including because they provide routine and useful information for APC (specifically, wafer-to-wafer control). Two embodiments of in-line reflectometry for film thickness measurements will be described in this section, one for use in CMP and the other for epi film growth.

Reflectometry is used to monitor and control film thickness in CMP operations. When CMP is used to planarize and remove part of a blanket film, such as in oxide CMP, there is no detectable endpoint, since no new films are exposed. The only way to monitor and control such a process is by means of a sensor that measures the thickness of the film. This is a very difficult task for a slurry-covered wafer that is in motion, hence the measurement is performed in-line in the rinse station of the CMP tool.

A commercially available reflectometry-based sensor (e.g., Ref. 52) is currently being used for CMP tool monitoring. Its primary benefits are as follows:

- Provides thickness measurement data for every product wafer, required for rapid feedback control of the CMP process
- Performs measurements in parallel to the processing of the next wafer, hence not affecting system throughput unless a very large number of measurements is required

In-water measurement capability obviates need to clean and dry wafers before measurements

Eliminates additional cleanroom space and labor required for off-line measurements

Only one component, the measurement unit, has to be integrated into the polisher. The compact size of this unit, with a footprint only ~40% larger than the wafer, enables easy integration into the process equipment. Two such implementations in commercial CMP tools are represented in Figures 20 and 21.

Two different delivery system principles are applied for the integration of the measurement system into OEM tools. In one case (Fig. 20) the wafer handler transfers wafers down from the wafer-loading station to the water tub of the measuring unit and back. In another configuration (Fig. 21), the measurement unit replaces the unload water track of the polisher. It receives the wafer, performs the measurement process, and delivers the wafer to the unload cassette. In both cases, the wafer is wet during the measurement.

A second commercially available implementation of reflectometry (in this case using an IR source and nonnormal incidence) is the use of FTIR measurement of epi thickness. The in-line measurement of epi thickness has been achieved by the integration of a compact FTIR spectrometer (53) to an Applied Materials Epi Centura cluster tool, as shown in Figure 22. The cool-down chamber top plate is modified to install a CaF_2 IR-transparent window, and the FTIR and transfer optics are bolted to the top plate. The IR beam from the FTIR is focused to a 5-mm spot on the wafer surface, and the specular reflection is collected and focused onto a thermoelectrically cooled mercury cadmium telluride (MCT) detector. Reflectance spectra can be collected in less than 1 s. Reference spectra are obtained using a bare silicon wafer surface mounted within the cool-down chamber. Epi thickness measurements are made after processing, while the wafers are temporarily parked in the cluster tool's cool-down chamber, without interrupting or delaying the wafer flow.

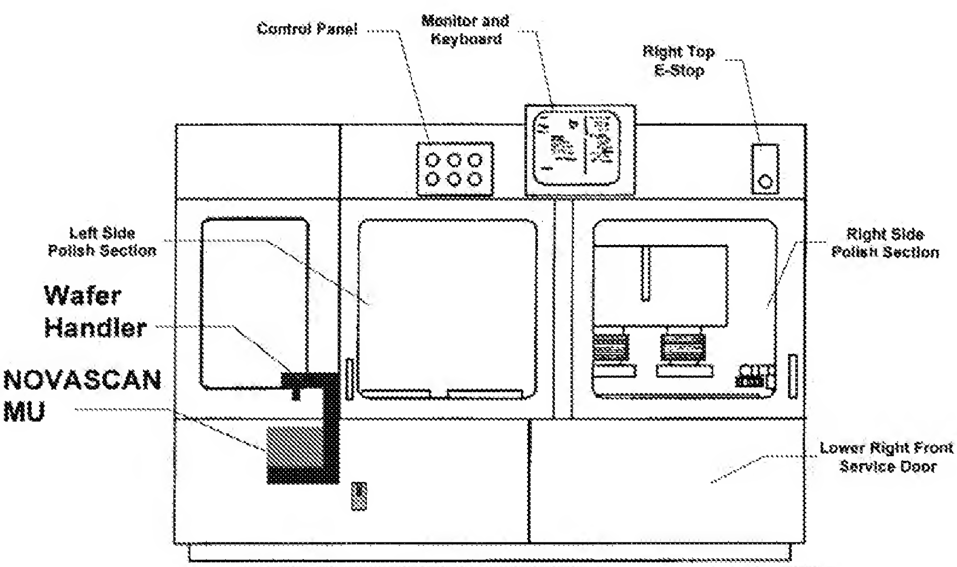

Figure 20 NovaScan system integrated in Strasbaugh model 6DS-SP planarizer. (From Ref. 51.)

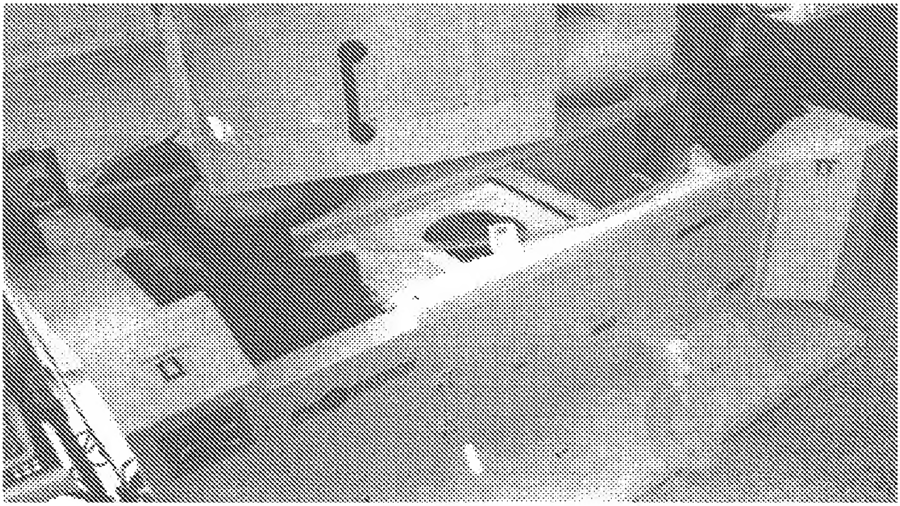

Figure 21 NovaScan in IPEC 372M and 472 polisher. (From Ref. 51.)

A simulated reflectance spectrum is computed from parametric models for the doping profile, the dielectric functions (DFs) of the epi film and substrate, and a multilayer reflectance model. The models for the wavelength-dependent complex DFs include dispersion and absorption due to free carriers, phonons, impurities, and interband transitions. The models are tailored to the unique optical and electronic properties of each material. The reflectance model computes the infrared reflectance of films with multilayered and graded compositional profiles using a transfer matrix formalism (54,55). The model parameters are iteratively adjusted to fit the measured spectrum.

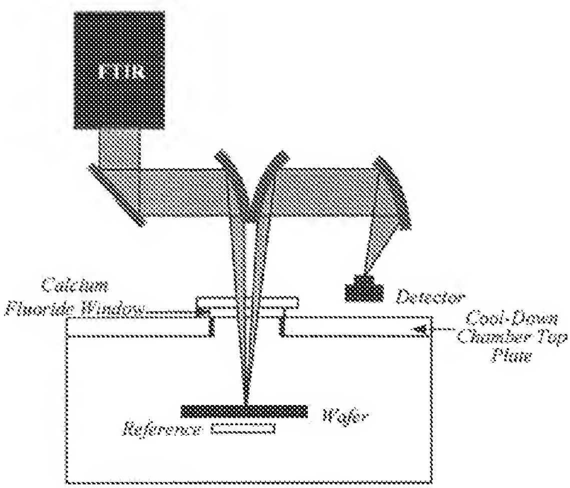

Figure 22 Configuration of On-Line Technologies, Inc., FTIR on Applied Materials' Centura 5200. (From Ref. 52.)

Gauge tests demonstrate the relative accuracy of this first-principle analysis of epi layer thickness to be in the range of 0.5–2 nm (5–20 Å). Comparison to destructive SIMS and SRP measurements shows the absolute accuracy to be within the accuracy of these standard measurements.

b. Interferometric Technique

Theory of operation. Interferometry is a well-established technique for the optical measurement of thin, optically transparent films. Some of the light impinging on such a thin film reflects from the top of the film and some from the bottom of the film. The light reflected from the bottom travels farther, and the difference in path length results in a difference in phase. After reflection, the light following the two paths recombines and interferes, with the resulting light intensity a periodic function of the film thickness. The change in film thickness for one interferometric cycle is $\lambda/2n\cos\theta$, where λ is the observation wavelength, *n is the index of refraction of the film, and* θ *is the angle of refraction within the film.*

Full-wafer imaging sensor. The full-wafer imaging (FWI) sensor (56) is a novel sensor developed in the early 1990s (57) based on this interferometric technique. It uses an imaging detector to make spatially resolved measurements of the light reflected from the wafer surface during etching or deposition processes. This sensor takes advantage of the fact that the reflectivity of a thin film on the wafer surface is generally a function of the thickness of the film. By quantifying the changes in reflectivity as the film thickness changes, the FWI sensor determines spatially resolved etching or deposition rate, rate uniformity, spatially resolved endpoint, endpoint uniformity, and selectivity. These measurements are performed on every wafer, providing both real-time endpoint and run-by-run data for process monitoring and control.

The operation of this particular sensor relies on a number of optical phenomena:

Optical emission: Optical emission from the plasma is the preferred light source for FWI sensors because it is simpler than using an external light source and it allows direct detection of optical emission endpoint. If plasma light is not available, an external light source can be added. A narrow-bandpass filter is used to select the measurement wavelength. Different wavelengths are best suited to different types of process conditions, the most important characteristics being the intensity of the plasma optical emission as a function of wavelength, the film thickness, and the film's index of refraction. In general, a shorter wavelength gives better rate resolution, but cannot be used in certain situations; e.g., a 0.3-μm-thick layer of amorphous silicon is typically opaque in the blue but transparent in the red.

Interferometry for transparent thin films: In practice, during an etching or deposition process, the intensity of light reflected from the wafer surface varies periodically in time. The interferometric signal is nearly periodic in time in most processes because the process rate is nearly constant, even though the signal is strictly periodic in film thickness rather than in time.

Interferometry for trench etching: In trench etching, the interference is between light reflected from the top of the substrate or mask and light reflected from the bottom of the trench. A coherent light source, e.g., a laser, must be used because the interference is between two spatially distinct positions. Etching rate is calculated using the same types of techniques discussed earlier for thin-film interferometry. Endpoint time is predicted by dividing the desired trench depth by the measured etching rate.

Reflectometry for nontransparent films: Light impinging on a nontransparent film reflects only from the top of the film, so there is no interference. However, the reflectivity of the nontransparent film that is being etched is different from the reflectivity of the underlying material. Thus the intensity of reflected light changes at endpoint. This method is typically applied to endpoint detection in metal etching.

From a system viewpoint, the FWI sensor requires a high data-acquisition rate and uses computationally intensive analyses. So the typical configuration consists of a high-end PC, advanced software, and one or more independent CCD-based sensor heads interfaced to the computer via the PCI bus. Each sensor head records images of a wafer during processing, with each of the few hundred thousand pixels of the CCD acting as an independent detector. The full images provide visual information about the wafer and the process, while the signals from thousands of detectors provide quantitative determination of endpoint, etching or deposition rate, and uniformity. The simultaneous use of thousands of independent detectors greatly enhances accuracy and reliability through the use of statistical methods. The FWI sensor can be connected to the sensor bus by adding a card to the PC. Connecting the sensor head directly to the sensor bus is not practical, due to the high data rate and large amount of computation.

Figure 23 shows a schematic diagram of the FWI sensor head installation. The sensor head is mounted directly onto a semiconductor etching or deposition tool on a window that provides a view of the wafer during processing. A top-down view is not necessary, but mounting the sensor nearly parallel to the wafer surface is undesirable because it greatly reduces spatial resolution, one of the technique's principal benefits. For both interferometry and reflectometry, spatially resolved results are determined by applying the same calculation method to hundreds or thousands of locations distributed across the wafer surface. These results are used to generate full-wafer maps and/or to calculate statistics for the entire wafer, such as average and uniformity.

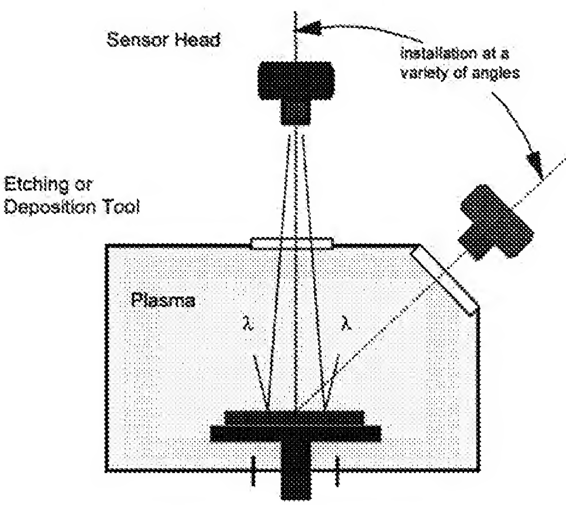

Figure 23 Full-wafer imaging sensor head mounting. (From Ref. 56.)

Several methods can be used to find the etching or deposition rate from the periodic interference signal. The simplest way is to count peaks, but this is accurate only if there is a large number of interferometric cycles, which is not common in most semiconductor processes. For example, a 0.3-μm-thick layer of polysilicon contains only 3.8 interferometric cycles. The accuracy of simple peak counting is one-half of a cycle, which is only 13% in this example. The accuracy can be improved somewhat by interpolating between peaks, but the accuracy is still fairly low. In addition, false peaks caused by noise in the signal often plague peak-counting methods.

A more accurate way to determine rate is to multiply the change in film thickness per interferometric cycle by the frequency (number of cycles per second). The simplest way to find the desired frequency is to use a fast Fourier transform (FFT) to convert from the time domain to the frequency domain. A local maximum in the signal versus frequency then specifies the frequency to be used in the rate calculation. Accuracy can be further increased by starting with an FFT to provide an initial guess of the frequency and then fitting the signal versus time to an empirical function that models the physical signal. This combined method is more accurate than the FFT alone if there are few cycles, if the interferometric signal is not a pure sinewave, or if the signal-to-noise ratio is low—all of which occur commonly in semiconductor processing. In either method, a frequency window can be used to designate which maximum in the FFT is used to calculate rate. This is a useful way to measure selectivity in etching processes where two materials, e.g., the mask and the film of interest, are etching simultaneously.

For transparent thin films, endpoint can be detected or predicted. The detection method relies on the fact that the periodic modulation of reflected light intensity ceases at endpoint. Endpoint is found by detecting the deviation of the observed signal from an interferometric model. The prediction method uses the measured rate and the desired thickness change to predict the endpoint time. Prediction is the only available endpoint method for deposition processes. It is also necessary in those etching processes where the film is not completely removed.

The FWI technique has been used on devices with feature sizes down to 0.1 μm, aspect ratios up to 50:1, percent open area as low as 5%, film thickness greater than 2 μm, and substrate sizes larger than 300 mm. Endpoint, etching or deposition rate, and uniformity can be monitored for a variety of transparent thin films, including: polysilicon, amorphous silicon, silicon dioxide, silicon nitride, and photoresist. For nontransparent materials, such as aluminum, tungsten silicide, chrome, and tantalum, rate cannot be measured directly, but spatially resolved etching endpoint and thus endpoint uniformity have been determined.

Examples of the use of FWI are shown in the following figures. Figure 24 is an example of the signals from three different CCD pixels recorded during a polysilicon gate etching process. Each pixel imaged a small, distinct region; an image of the wafer is included to indicate the position of these pixels. Two of the pixels are on the wafer and display a periodic signal due to the change in thickness of the thin film. The pixel off the wafer shows the optical emission signal, which rises at endpoint. Analysis of the periodic signal is used to determine rate and/or endpoint, while analysis of the optical emission signal is used independently to detect the average endpoint time for the entire wafer.

Figure 25 is an example of a full-wafer etching-rate-uniformity surface plot. The plot was generated from rate calculations at 4000 locations on a rectangular grid covering the wafer. Two trends are evident. First, the etching rate at the center of the wafer is lower than at the edge. Second, variations within each die are visible as a regular array of peaks and valleys in the etching-rate surface plot. The deepest of these valleys go all the way to

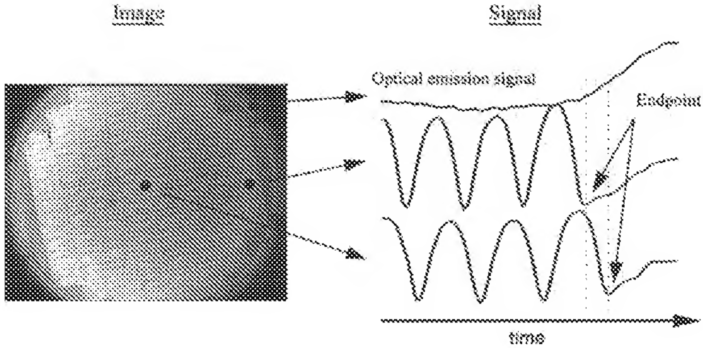

Figure 24 Signal from three positions: two on the wafer and one off the wafer. (From Ref. 56.)

zero and correspond to areas of pure photoresist mask, which did not etch appreciably in this high-selectivity process.

Figure 26 is an example where an FWI sensor was used to automatically monitor every product wafer. Results for each wafer were determined and displayed while the next wafer was being loaded into the processing chamber. The figure shows the etching rate and uniformity for four consecutive product wafer lots. The process was stable (no large fluctuations in rate or uniformity) but not very uniform (7%, 1σ). Furthermore, pattern-dependent etching is clearly evident. At the beginning of each lot, several bare silicon warm-up wafers and one blanket (not patterned) wafer were run, and then the patterned product wafers were run. The blanket wafers etched about 10% slower and

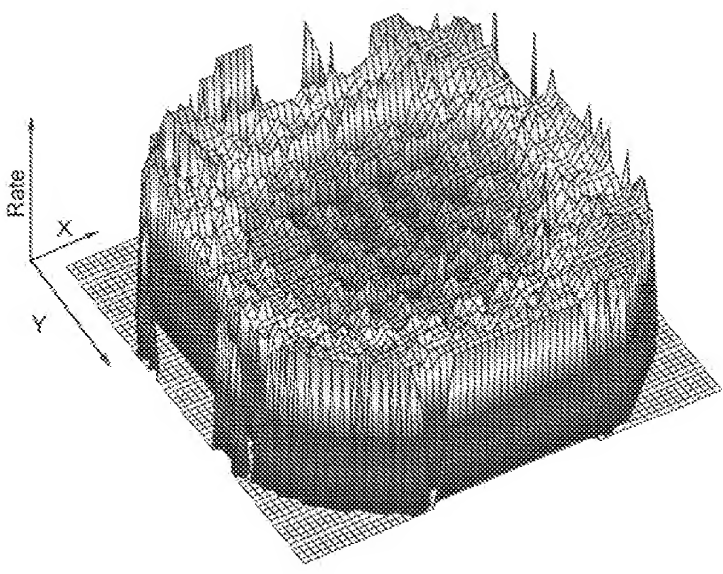

Figure 25 Full-wafer etching-rate map. Average = 2765 Å/min, uniformity = 3.9% $1-\sigma$. (From Ref. 56.)

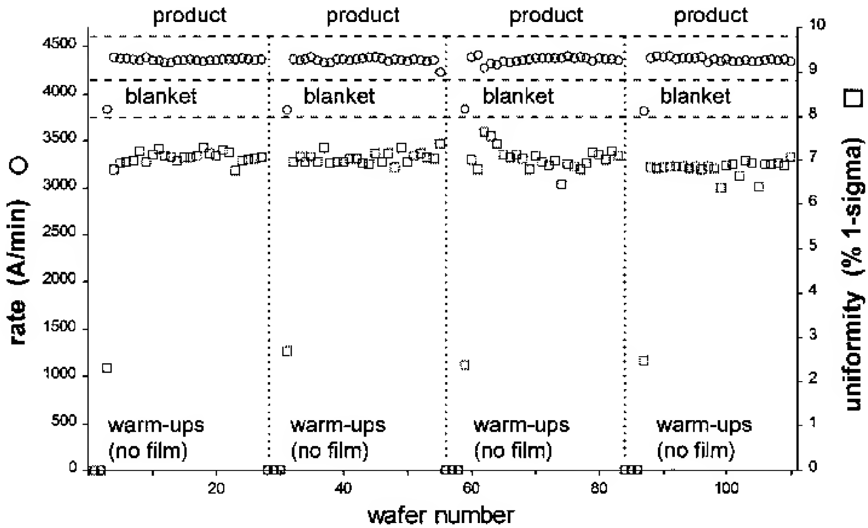

Figure 26 Rate and uniformity for four product wafer lots. (From Ref. 56.)

much more uniformly than the product wafers. The difference between the blanket and product wafers demonstrates the need to use real product wafers to monitor a process.

Sensor calibration has been achieved by a comparison between FWI sensors and ex situ film-thickness metrology instruments. The agreement is generally good, even though the two systems do not measure exactly the same thing. The FWI measures dynamic changes in film thickness, while the ex situ instruments measure static film thickness. It is typical to take the thickness-before minus thickness-after measured ex situ and divide this by the total processing time to get the ex situ rate and uniformity values that are compared to the rate and uniformity measured in situ by the FWI.

Integration to the processing tool is required to obtain the benefits provided by an FWI sensor. There are two main technical issues. First, a window that provides a view of the wafer during processing is required. Between wet cleans, this window must remain transparent enough that the wafer stays visible. Second, communication between the tool's software and the FWI sensor's software is useful to identify the process and wafer/lot and to synchronize data acquisition. Both of these technical needs must be met whether the FWI runs on a separate computer or on a subsystem of the tool controller.

The FWI sensor provides different benefits to different users. In R&D, it provides immediate feedback and detailed information that speeds up process or equipment development and process transfer from tool to tool. In IC production, every product wafer can be monitored by the FWI sensor so that each wafer serves as a test wafer for the next. This means that fewer test, monitor, qualification, and pilot wafers are required—a significant savings in a high-volume fab. Also, fewer wafers are destroyed before faults or excursions are detected, and data is provided for statistical process control (SPC) of the process.